Trends in Arctic sea ice drift and role of wind forcing: 1992–2009

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[1] We examine the spatial trends in Arctic sea ice drift speed from satellite data and the role of wind forcing for the winter months of October through May. Between 1992 and 2009, the spatially averaged trend in drift speed within the Arctic Basin is 10.6% ± 0.9%/decade, and ranges between −4% and 16%/decade depending on the location. The mean trend is dominated by the second half of the period. In fact, for the five years after a clear break point in March 2004, the average trend increased to 46% ± 5%/decade. Over the 1992–2009 period, averaged trends of wind speed from four atmospheric reanalyses are only 1% to 2%/decade. Regionally, positive trends in wind speed (of up to 9%/decade) are seen over a large fraction of the Central Arctic, where the trends in drift speeds are highest. Spatial correlations between the basin-wide trends in wind and drift speeds are moderate (between 0.40 and 0.52). Our results suggest that changes in wind speed explain a fraction of the observed increase in drift speeds in the Central Arctic but not over the entire basin. In other regions thinning of the ice cover is a more likely cause of the increase in ice drift speed. **Citation:** Spreen, G., R. Kwok, and D. Menemenlis (2011), Trends in Arctic sea ice drift and role of wind forcing: 1992–2009, *Geophys. Res. Lett.*, *38*, L19501, doi:10.1029/2011GL048970.

1. Introduction

[2] Arctic sea ice underwent profound changes in recent years. The annual mean sea ice extent decreased by −3.7% ± 0.2%/decade between 1979 and 2007 with an enhanced negative trend of −10.1% ± 0.7%/decade between 1996–2007 [*Comiso et al.*, 2008]. Sea ice thickness decreased by 1.6 m or 53% for the ICESat period (2003–2008) compared to early submarine measurements between 1958–1976 [*Kwok and Rothrock*, 2009]. During the 2003–2008 period, Arctic sea ice volume decreased by 42% and 21% for fall (Oct/Nov) and winter (Feb/Mar), respectively [*Kwok et al.*, 2009].

[3] These changes are accompanied by an increase in the sea ice drift speeds seen in drifting buoys. *Rampal et al.* [2009] report an overall increase of the mean Arctic drift speed of 0.6 cm/s/decade for the 1979–2007 period. The winter buoy speed increased by 0.74 cm/s/decade or 17%/decade and the summer speed by 0.59 cm/s/decade or 8.5%/decade. *Hakkinen et al.* [2008] observe an increase in Central Arctic drift speed since 1950 using a combined buoys and drifting ice stations dataset.

[4] Ice motion is forced by the wind and, to a lesser degree, the ocean currents. Sea ice drifts at roughly 1% to 2% of the surface wind speed (Figure S1 in the auxiliary material).[1] The wind to ice drift speed relation is linear for most wind speeds and only becomes nonlinear for small wind speeds [*Thorndike and Colony*, 1982; *Leppäranta*, 2005]. The exact sea ice speed is also influenced by atmosphere and ocean drag coefficients and the internal ice stress. These factors are controlled by the thickness, deformation, and compactness of the ice cover. *Rampal et al.* [2009] did not find a trend in surface wind speed and thus concluded that changes in the ice cover changes play a dominant role in explaining the observed sea ice drift speed trend. On the other hand, *Hakkinen et al.* [2008] find an increase in both drift speed and wind stress during the period 1950–2006. They attribute the change in drift speed to the positive trend in NCEP wind stress caused by a shift of storm tracks to higher latitudes.

[5] In this note, we examine the correspondence between the spatial trends in drift speed from satellite-derived ice drift and those of wind speed from four different atmospheric reanalyses for the years 1992 to 2009. The coverage of satellite ice motion allows us to explore the space-time variability of these trends. Our focus is on changes in the surface (10 m) wind speed and its connection to the observed ice drift speed. The following questions are addressed: (1) Are there trends in drift speed for the 17 winters (Oct.–May) between 1992 to 2009 and how does drift speed evolve during this time period? (2) Are there trends in surface wind speed over the sea ice during the same time period? (3) What is the spatial structure of the sea ice/wind speed trends and how do they correlate in space and time? (4) Does wind speed play a role in the observed increase in ice drift speed over this period?

2. Methods and Data

[6] We compare sea ice drift speeds derived from SSM/I satellite data with 10 m-wind speeds from four atmospheric reanalyses. Calculations are done with the magnitude of wind and ice drift ($s = \sqrt{u^2 + v^2}$); directional changes are not considered. Ice and wind speed anomalies are computed by removing the mean seasonal cycle in the 17-year record. Trends are calculated in a least square sense from these daily anomalies on the original data grids. Significance ($p > 0.99$) is measured using the Student's t-test. For presentation, results are projected onto a polar stereographic grid. Wind data were restricted on a daily basis to areas covered by sea ice using SMMR/SSMI NASA-Team ice concentrations [*Cavalieri et al.*, 1996; *Meier et al.*, 2006] and trends are

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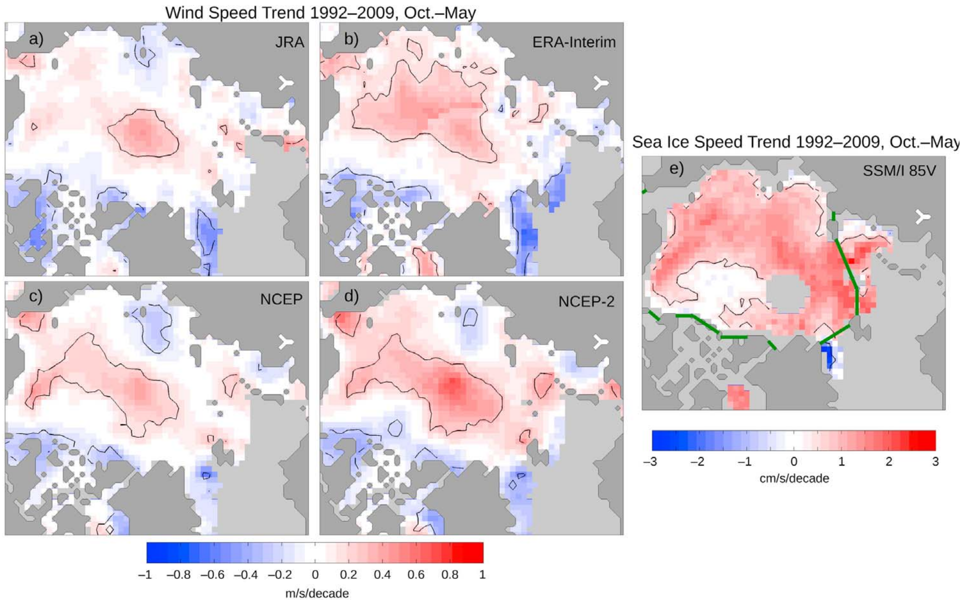

Figure 1. Spatial trends in wind and sea ice drift speeds for the winters (October–May) 1992/1993 to 2008/2009 (see Figure S3 for year-round wind trends). (a–d) The trends in 10 m wind speed from the four atmospheric reanalyses: JRA, ERA-Interim, NCEP, and NCEP-2. (e) Drift speed trends from satellite ice motion. Statistically significant trends are inside the black contour ($p > 0.99$). Thick green limits delimit boundaries of the Arctic Basin.

only calculated for grid points covered with sea ice >60% of all days. Trend averages for both ice drift and wind are calculated for the area covered by ice drift data inside the Arctic Basin as defined by the green boundaries in Figure 1e.

2.1. Sea Ice Drift

[7] Sea ice motion is derived from microwave measurements between October and May obtained by the Special Sensor Microwave Imager (SSM/I). Details of the sea ice tracking procedure and an assessment of the data quality are discussed by *Kwok et al.* [1998]. Briefly, the maximum cross-correlation of sub-images of daily 85.5 GHz brightness temperature (TB) maps and in its surroundings shifted sub-images of the TB map of the following day are determined. No interpolation of gaps was done and no external data (i.e., buoy drift or wind data) were used in the construction of the motion fields. We did not use motion estimates from the summer months because of the gaps in the observations.

2.2. Surface Wind

[8] Surface wind data (10 m height) from four different reanalyses are used: 1) JRA from the Japan Meteorological Agency (JMA) (combined Japanese 25-year (JRA-25) and JMA Climate Data Assimilation System (JCDAS) reanalysis) has a nominal 110-km grid spacing (T106) and starts in 1979 [*Onogi et al.*, 2007]. 2) ERA-Interim from the European Centre for Medium-Range Weather Forecasts (ECMWF) has a nominal 79-km grid spacing (T255) and starts in 1989 [*Simmons et al.*, 2007; *Uppala et al.*, 2008]. 3) NCEP and 4) NCEP-2 from the US National Center for Environmental Prediction (NCEP) have a nominal 180-km grid spacing (T62) and start in 1948 and 1979, respectively.

3. Trends in Wind and Ice Drift Speeds

3.1. Spatial Patterns

[9] Figure 1 shows maps of the 1992–2009, Oct.–May 10 m wind speed trend over sea ice from JRA (a), ERA-Interim (b), NCEP (c), and NCEP-2 (d) together with the sea ice drift speed trend from satellite ice motion (e). Black contours delineate areas with statistically significant trends (confidence level: 99%).

[10] All four reanalyses show positive trends in the Central Arctic near the North Pole (up to 9%/decade). Negative trends are seen in the Canadian Archipelago and adjacent parts of the Lincoln and Eastern Beaufort Sea, in the Greenland Sea south of the Fram Strait, and parts of the Barents and Kara Seas. There are, however, also differences in the spatial pattern. JRA has a smaller region with positive trends in the Central Arctic and negligible trends in the Western Beaufort Sea compared to what is seen in the other three reanalyses. ERA-Interim does not have a region of negative trend around the New Siberian Islands that is present in the other reanalyses. ERA-Interim also shows a distinct arc inside the positive trend region, which is likely an artifact of data assimilation at high northern latitude. The spatial cross-correlation between the four wind trend maps, between 0.54 and 0.92, highlight the similarity in the four analyses. Even though there are large differences in the mean wind speed of up to 1.7 m/s (4.8 to 6.5 m/s) between the reanalyses the wind trends do agree well.

[11] Trends in ice drift speed (Figure 1e) are positive and statistically significant over a large fraction of the Arctic

Table 1. Trends With Error Estimates (One Standard Deviation) in Wind and Sea Ice Drift Speeds in cm/s/decade in the Arctic Basin[a]

	Oct–May				
Wind	92–09	92–00	00–09	79–09	Jan–Dec 92–09
JRA	5 ± 3	**−32** ± 11 −6% ± 2%	7 ± 9	−1 ± 1	−5 ± 2
ERA-Interim	**13** ± 3 2.1% ± 0.5%	**−58** ± 10 −7% ± 2%	**28** ± 9 5% ± 1%		−1 ± 2
NCEP	**7** ± 3 1.4% ± 0.6%	**−32** ± 9 −7% ± 2%	14 ± 8	−1 ± 1	−1 ± 2
NCEP-2	**14** ± 4 2.2% ± 0.7%	**−47** ± 14 −7% ± 2%	25 ± 11	**6** ± 2 0.9% ± 0.3%	2 ± 3
	Oct–May				
Ice Drift	92–09	92–00	00–09		
JPL	**0.94** ± 0.08 10.6% ± 0.9%	**−0.5** ± 0.2 −6% ± 3%	**2.5** ± 0.2 27% ± 2%		
Ifremer	**0.79** ± 0.07 12% ± 1%	**−0.5** ± 0.2 −8% ± 4%	**1.4** ± 0.2 21% ± 3%		

[a]For significant trends ($p > 0.99$, marked in bold) the change in %/decade (in reference to the complete period mean) is given in the second row. Ifremer ice drift trends are for October to April periods only (instead of Oct.–May). More year-round (Jan.–Dec.) wind trends can be found in Table S1.

Basin. Only parts of the Canada Basin and Greenland Seas show negligible or negative drift speed trends. Highest drift speed trends occur in the vicinity of the North Pole (~16%/decade), roughly coinciding with the positive wind speed trend patterns at the same location. For some areas like the Lincoln Sea or around the New Siberian Islands, however, drift speed trends are positive despite the fact that wind speed trends are negative for the same area. The spatial correlation coefficient between drift speed trends and wind speed trends is between 0.40 (NCEP) and 0.52 (NCEP-2; 0.46 for JRA, 0.42 for ERA-Interim).

[12] Trends of ice drift speeds obtained from merged QuikSCAT/SSMI data (from CERSAT/Ifremer [*Girard-Ardhuin et al.*, 2008]) also show a very similar spatial distribution (Table 1, last row and Figure S2); this lends support to the validity of our results.

[13] Remarkably all four reanalyses show a negative wind speed trend in Fram Strait, which corresponds well to the negative trend in satellite ice drift speed there. This is consistent with findings from *Kwok* [2009] and *Spreen et al.* [2009], who report no significant change in Fram Strait sea ice area and volume transport.

[14] In the following we will show figures for the NCEP dataset only (due to its widespread usage) but give numbers for all four reanalyses.

3.2. Evolution in Time

[15] All four atmospheric reanalyses show small positive trends (5 ± 3 to 14 ± 4 cm/s/decade or 0.8% ± 0.6% to 2.2% ± 0.7%/decade) in wind speed during October to May between 1992 and 2009 (Table 1) inside the Arctic Basin. But, this trend is significant for only three (ERA-Interim, NCEP and, NCEP-2) of four reanalyses. Also if the time period is extended to 1979–2009 only very small (≤|6| cm/s/decade or ≤1%/decade) wind speed trends can be found (Table 1). If the complete years (Jan.–Dec.) 1992–2009 are considered, no significant mean wind speed trend is evident within the Arctic Basin (Table 1 and Figure S3).

[16] Compared to the mean 1992–2009 trend in sea ice drift speed in the Arctic Basin of 0.94 ± 0.08% cm/s/decade or 10.6% ± 0.9%/decade, these wind trends are small.

[17] Figure 2 shows the time series for the Arctic Basin (see Figure 1e) wide anomalies of NCEP wind (a) and of satellite sea ice drift speed (c). While the yearly winter mean wind time series (blue) shows little variability (σ = 0.1 m/s) the drift speed time series shows a strong increase during the years 2003/2004–2008/2009 and has two distinct minima in 1999/2000 and in 2003/2004. The 1999/2000 minimum coincides with a wind speed minimum. Both the wind and drift speed time series show comparable negative trends during the first half (8 winters 92/93 to 99/00) of the period (see Table 1). During the second half (9 winters 00/01 to 08/09) both trends are positive but the wind trend is small while the ice drift trend of 27% ± 0.2%/decade dominates the overall time series.

[18] Since there is a distinction in the trends in ice drift between the first and second half of the time series, we use the method of *Tomé and Miranda* [2004] to determine a clear break point in a more quantitative manner. The method minimizes the residual differences of two connected trend segments separated by the break point. In this case, the March 2004 was identified as the break point. Between October 1992 and March 2004 the ice drift time series does not have a significant trend (−0.2 ± 0.1 cm/s/decade), while the drift time series shows a very strong positive trend of 4.4 ± 0.5 cm/s/decade or 46% ± 5%/decade between March 2004 to May 2009 (black line in Figure 2c). Regardless of the chosen location of the break point in the mean NCEP wind time series, the trends do not exceed |6%|/decade in the two segments.

[19] Figure 2b and d show the 1992–2009 wind and ice drift seasonal cycle for October to May. NCEP winds stay fairly constant at about 5 m/s during winter months October to January (JRA, ERA-Interim, and NCEP-2 ≥6 m/s). Thereafter wind speeds reduce towards spring and summer. The seasonal cycle of drift speed shows a different behavior and follows the ice freeze-up/melting cycle: drift speeds are highest in October, at the end of the summer, and thereafter decrease till the maximum sea ice freeze-up in March. With the beginning of the melting season in April drift speeds increase again.

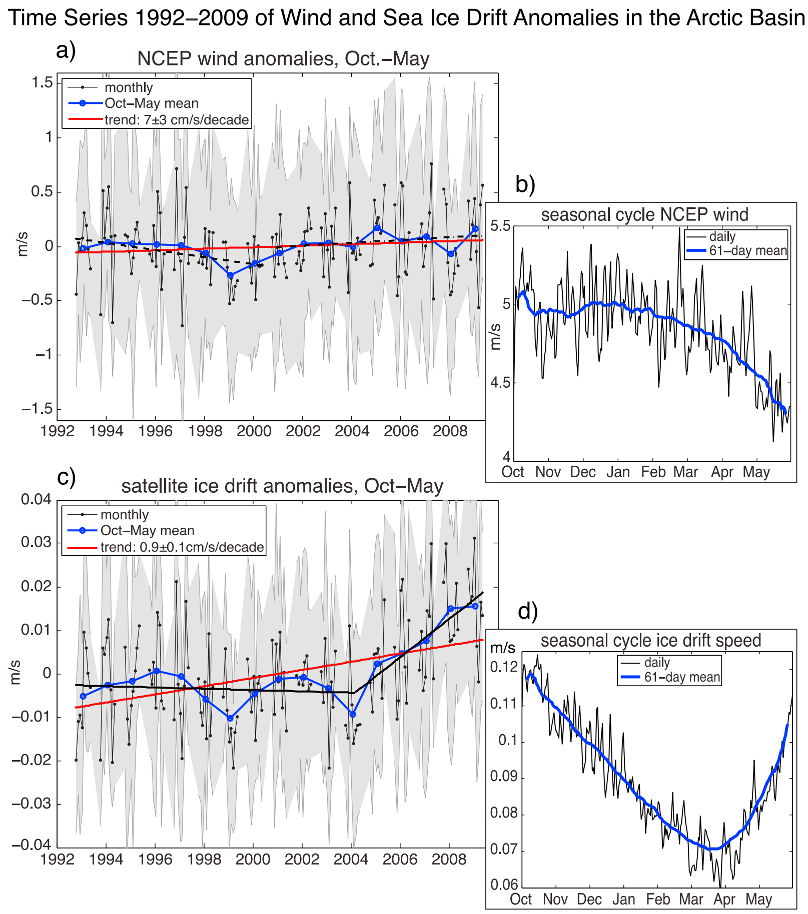

Figure 2. (a) Time series of Arctic October–May NCEP wind speed anomalies from October 1992 to May 2009 in the Arctic Basin. Black line: monthly data together with the standard deviation as gray shaded area; blue line: yearly data; red line: least square fit based on the daily anomalies; dashed and dashed-dotted lines: trends for 92–00 and 00–09, respectively. (b) October–May seasonal cycle of NCEP wind speeds. Black line: daily data; blue line: 2-month running mean. (c, d) As in Figures 2a and 2b but for SSM/I satellite sea ice drift speed; the thick black line in Figure 2c shows the trend segments before and after the break point in March 2004.

[20] Figure 3 shows the trends in NCEP wind and satellite sea ice drift speed for the first half (92/93–99/00; Figure 3, top) and second half (00/01–08/09; Figure 3, bottom) of the time series. Both wind and drift speed during Oct.–May (Figures 3a and 3b), show the shift from a mainly negative regime to a mainly positive regime in the second half. The spatial cross-correlation coefficient for 1992–2000 between wind speed and drift speed trend maps is low (0.04 for NCEP, 0.25 for JRA, 0.17 for ERA-Interim, and 0.07 for NCEP-2). For 2000–2009, the correlation coefficients are higher (0.40 for NCEP, 0.40 for JRA, 0.62 for ERA-Interim, and 0.46 for NCEP-2) and show that wind is likely a contributor to the observed ice drift speed increase and explains about 22% of the spatial drift trend variance. Many regions with positive drift speed trend, however, show zero or negative wind speed trends, e.g., the East Siberian and Laptev Seas during 2000–2009. During summer (Figure 3c) wind trends are mainly negative for the complete time period.

4. Discussion

[21] For the 17 winters (Oct.–May) between 1992 and 2009 Arctic Basin wide sea ice drift speed from SSM/I satellite radiometry increased by 0.94 ± 0.08 cm/s/decade or 10.6% ± 0.9%/decade (magnitude of sea ice drift; directional changes are not considered). This can be compared with the longer term trend (1979–2007) of 0.7 ± 0.1 cm/s/decade that was derived using buoy drifts [*Rampal et al.*, 2009]. The increase in speed did not occur monotonically but was mainly restricted to the second half of the period. The ice drift time series shows a clear break point in March 2004. Prior to that there is no significant ice drift trend and after March 2004 the trend increases to 4.4 ± 0.5 cm/s/decade or 46% ± 5%/decade. This corresponds to rapidly thinning and ice loss of thick multiyear ice since 2003 observed in the submarine and ICESat data [*Kwok and Rothrock*, 2009]. Also the winter sea ice area decreased more rapidly after 2002 in the Arctic Basin (Figure S6b). The trends in drift speed are not spatially homogeneous. Large parts of the Canada Basin show no significant trend. In the western part of Fram Strait the 92–09 drift trend is also small suggesting that the sea ice outflow did not change significantly.

[22] During the same 17 winters, trends in 10-m wind speed obtained from four different atmospheric reanalyses for the same region are between 5 ± 3 to 14 ± 4 cm/s/decade, that is, a maximum of 2.2% ± 0.7%/decade, which is con-

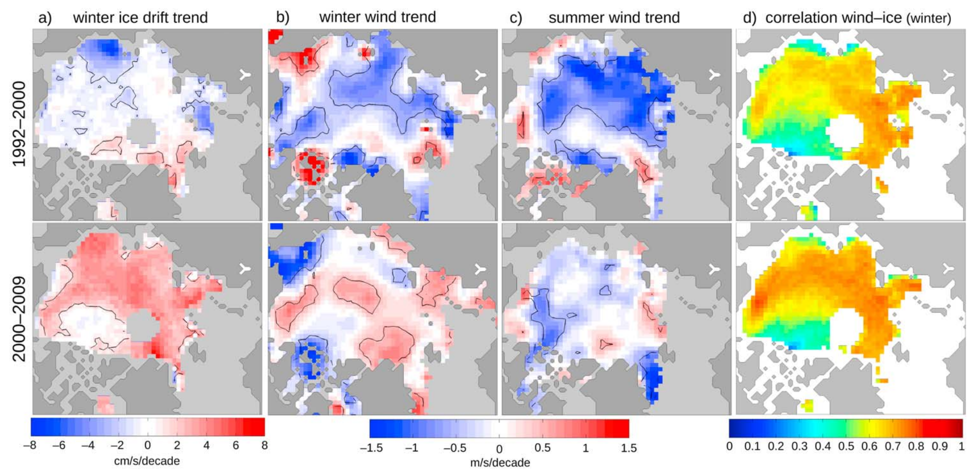

Figure 3. Trends in (top) 1992–2000 and (bottom) 2000–2009 (a) winter (Oct–May) ice drift speed, (b) winter (Oct–May) and (c) summer (Jun–Sep) NCEP wind speed. (d) Correlation between detrended winter wind and drift speed time series at each grid point. Trends inside the black contour are significant ($p > 0.99\%$). (Wind speed trend maps for JRA, ERA-Interim, and NCEP-2 can be found in Figure S5.)

siderably smaller than the drift speed trend. Since the wind trends are much smaller, the observed ice drift speed increase is not explained by a linear relationship between wind and sea ice drift. This finding holds even if the time period is extended to 1979. For the summer months, not available with this ice drift dataset, wind trends are mainly negative (Figure 3c) and wind unlikely would contribute to positive trends in drift speed during summer.

[23] As wind is the main driver of ice drift, the patterns of mean wind and drift speeds in the Arctic are highly correlated ($R \approx 0.8$, see Figure S4). The response of sea ice to wind forcing, however, is not homogeneous over the Arctic Ocean (see Figure S1). Figure 3d shows the correlation coefficient between the detrended NCEP wind and sea ice drift time series for every grid point. The correlation is high in the Central Arctic, where both wind and drift speed show positive trends (Figure 1), suggesting that the wind plays a role in the observed ice drift speed increase.

[24] The correlation is lower in regions where coastlines and islands affect ice movement and in areas with thicker ice (higher strength), e.g., north of the Canadian Archipelago. In these regions, however, wind trends are mainly negative while ice drift trends are still positive suggesting changes in the ice cover or the ocean. Sea ice concentration (IC) trends in the Arctic Basin are negative (−1.6% ± 0.2%/decade during 1992–2009). The Barents Sea, Chukchi Sea, and the Eurasian side of the Arctic Basin show the biggest IC trends (see Figure S6). In these regions, e.g., the Northern Barents, Kara, Laptev, and East Siberian Seas, drift speed trends are mainly positive while the wind speed trends are negative. Here a less compact and thinner ice cover, which is more susceptible to wind, likely has contributed to the drift speed increase. The Arctic sea ice thickness is decreasing since at least the 1980s [*Kwok*, 2009] and caused a weaker ice cover, which is more susceptible to wind forcing. During the second half of our time period both the wind-ice drift correlation (Figure 3d) and ice drift speed to wind speed ratio increased (Figure S1) compared to the first half. This coincides with the strong increase in sea ice drift speed during that time.

[25] We are not able to directly quantify the contribution of a thinning to the observed trends, as a long-term record of the spatial distribution of Arctic ice thickness does not exist. Coupled sea ice and ocean models could be useful in understanding of the detailed interaction and contribution of atmospheric, oceanic, and intrinsic sea ice changes on the observed ice speed increase.

[26] The dominant mode of Arctic sea level pressure (SLP) pattern, the Arctic Oscillation (AO), does not show a clear shift to another phase during 1992–2009 (see Figure S7) and thus cannot explain the changes in wind and drift speed trend patterns between the first and second half of the time series (Figure 3). However, the winter (Oct.–May) AO shows a small positive trend during 1992–2009. AO+ can be associated with a weak Beaufort Sea High and a strengthening of the Transpolar Drift and the opposite for AO− [*Stroeve et al.*, 2011], which is exactly what we observe (Figure S8a). The mean ice drift trend in the Arctic Basin during AO+ is 1.4 ± 0.1 cm/s/decade, that is, double the one during AO− (0.7 ± 0.1 cm/s/decade; Figures S8b and S8c).

[27] Our results also highlight that trends for both ice drift and wind speed are spatial variable. Trends vary (even change sign) over the Arctic Ocean and trends from single point measurements may not be representative for the entire Arctic.

5. Conclusions

[28] In conclusion, the Arctic Basin sea ice drift speed increase between 1992 and 2009 is much larger (10.6% ± 0.9%/decade) than the wind speed increase (~1.5%/decade). For many regions (e.g., Central Arctic), however, wind speed trends play a role in the observed drift speed changes. In other regions (e.g., near coastlines), where the wind trend is negative or neutral, changes in the ice cover, e.g., a thinner, less compact and weaker ice cover, are a more likely cause for the observed ice drift speed increase. The ice drift trend is strongest in the second half of the observed period (27% ± 2%/decade during 2000–2009; increases to 46% ± 5%/decade after 2004), concurrent with a strong

reduction in sea ice extent and thickness. The Arctic Basin-wide wind trend during that time period is at most 5% ± 1%/decade, however, reaches up to 20%/decade in the Central Arctic. *Rampal et al.* [2009] conclude that wind is not a major contributor to the observed ice drift speed trend and that changes in the sea ice cover play the dominant role. Our analysis points to a role for wind forcing, especially in the Central Arctic and in the latter half of our period.

[29] **Acknowledgments.** Distribution of atmospheric reanalysis data by the Japan Meteorological Agency (JMA), ECMWF, Reading, UK, and NOAA/OAR/ESRL PSD, Boulder, CO, USA are acknowledged. SSM/I data were obtained from the National Snow and Ice Data Center (NSIDC). We thank the three reviewers for useful comments. This work was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

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